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EVAPORATION RATE OF WATER FROM GLASS SURFACE UNDER NATURAL AND FORCED CONVECTION

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ABSTRACT

This article discusses the question of calculating of evaporation rate of water from glass surface at the final stages upon natural and forced convection at atmosphere pressure in isothermal conditions. Petri dish was used as glass surface. At the end of evaporation of single-component liquid (water) position of experimental points in the liquid weight–evaporation time plot deviates from linear dependence. This deviation characterizes gradual decrease in amount of evaporated moisture per equal time intervals and does not imply decrease in evaporation rate. The evaporation rate corresponds to the rate of mass transfer expressed in kg/(m^2·s). Water placed into Petri dish is referred to wetting moisture (free moisture), its evaporation rate equals to evaporation rate of water from free surface. Initial evaporation surface is the same as the surface of the water mirror placed into Petri dish. During evaporation water does occupy not the entire surface of the bottom of the Petri dish, but only a certain part of it, wherein evaporation surface (mass transfer surface) is the surface of water bordering on the air. Article accepted that relative variation of mass transfer surface area is proportional to relative variation of moisture weight with certain coefficient of proportionality. The proposed dependence in the first approximation is accepted to be linear. Calculated decrease in water weight in time with consideration for the introduced adjustment agrees with experimental data obtained under natural and forced convection. Evaporation rate increases during water heating and remains constant during overall evaporation process.

KEYWORDS: Evaporation of Water, Evaporation Rate, Natural Convection & Forced Convection

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Original Article

INTRODUCTION

Nowadays scientific and practical interest to evaporation of pure liquids and solutions is related with development of nanotechnologies, criminalistics, deposition of solid phase from weakly concentrated solutions, etc. Unavailability of unified approach to process of moisture loss in mathematical models leads to various interpretations of the obtained results. This work is devoted to searching for possible reasons of deviations between experimental data and calculations during evaporation of pure water under natural and forced convection in isothermal conditions.

RELATED WORK

Numerous publications are devoted to investigations into evaporation of pure liquids and solutions on solid surfaces (substrates) at various temperatures and pressures. Significant attention is paid to water (Lykov 1962; Boyarshinov et al. 1985; Zakharenko et al. 1998; Zakharenko et al. 2002; Renksizbulut, Yuan' 1983) and binary aqueous solutions (Saverchenko et al. 2011; Terekhov, Shishkin 2009; Lukashov 2003). Evaporation of

water from solutions with the aim of medical diagnostics is studied sufficiently well, since water is the main component of physiological solutions, in NaCl aqueous solutions, in solution of bovine serum albumin applied in laboratories as marker in gel chromatography and protein electrophoresis (Yakhno et al. 2010; Tarasevich, Pravoslavnova 2007). The monograph (Fuks 1958) presents data obtained in the Whytlow-Gray laboratory on evaporation of droplets of water, aniline, quinoline, and others with the size of 1–2 mm placed onto a pan of quartz microbalance. It was established that in all cases the droplet surface area decreased linearly with evaporation time despite decrease in the droplet volume by 100 times during overall experiment. The obtained result relates to study of a droplet of pure liquid from the surface of which evaporation takes place. While studying evaporation of a droplet placed onto heated solid surface, the researchers (Semenov et al. 2015;Gatapova et al. 2014) discovered that the mass flow from unit surface per unit time increased, especially at the last stage of droplet evaporation. Initial droplet volume was 100 µl.

This work discusses the question of calculating of evaporation rate of water from solid surface (substrate) at atmosphere pressure in isothermal conditions. Glass Petri dish was used as solid surface. It has been taken into account that glass is related to hydrophilic surfaces which are well wetted by water.

RESULTS AND DISCUSSIONS

According to the generally Rehbinder classification of forms of moisture connection with the material, water in Petri dish is referred to as wetting moisture, that is, free moisture, its evaporation rate equals to that of water from free surface. Evaporation of liquid is mass transfer process accompanied by phase transition of fluid from liquid state to vapor. In this regard, the evaporation rate is the rate of mass transfer. These ideas are not new; however, various concepts of evaporation rate are available in publications. In this case, while considering evaporation of water from glass surface, we will understand to the evaporation rate as to water amount evaporating from unit surface area per unit time, kg/(m^2·s), which completely agrees with the notion of mass transfer rate. The evaporation rate of free moisture is *const* during overall evaporation time and is described by linear function.

Mathematical models of water evaporation from glass surface under natural and forced convection were proposed in (Konstantinov et al. 2015;Korotkovaet al. 2016b), they were identified on the basis of experimental data on water evaporation at atmosphere pressure in isothermal conditions (Korotkova et al. 2016a;Danilchenko, Korotkova2016; Korotkova et al. 2016c). The obtained curves of water weight as a function of evaporation duration do not contradict with published experimental data according to which position of experimental points in the liquid weight–evaporation time diagram deviates from linear dependence at the end of evaporation of single component liquid (water, alcohol).

In the present work we assume that this deviation characterizes only gradual decrease in the amount of evaporating liquid per equal time intervals and does not imply decrease in evaporation rate.

Initial evaporation surface coincides with water surface in Petri dish since there exists certain thickness of water layer. During water evaporation, that is, its weight loss, water occupies not all bottom surface of Petri dish but a portion of it, and the evaporation surface is the water surface contacting with air. This surface is the surface of mass transfer.

In order to verify this assumption, we carried out experiment at ambient temperature comprised of evaporation of transparent (drinking) water and water slightly colored with manganese crystals in Petri dish (Figures 1–3). Displacement and variation of geometrical shape agree with experimental data in (Yakhno et al. 2010) where evaporation evolution of droplet with the size of 3 µl (microliter) is described.

Figure 1: Initial State of Water Colored With Manganese Crystals in Petri Dish

a) b) c) d) e)

Figure 2: Evaporation Evolution of Slightly Colored Water

a) b) c) d) d)

Figure 3: Evaporation Evolution of Non Colored Water

Let us assume that the drying speed is *const* for overall duration of water evaporation, that is, corresponds to evaporation of water from free surface. From the time when water begins to occupy the surface lower than the bottom surface of Petri dish, decrease in water weight leads to decrease in evaporation surface, that is, contact surface between water and air, which in its turn at equal time intervals leads to decrease in weight of water transferred into air as vapor. Let us assume that the decrease in the evaporation surface is proportional to the amount of evaporated water. When the evaporation surface approaches zero, the amount of evaporated moisture also approaches zero. Without evaporation surface there is no evaporated water because there is nothing to be evaporated.

Let us assume that the relative variation of mass transfer surface is proportional to the relative variation of moisture weight:

$$\frac{\Delta F}{F} \approx k \frac{\Delta W}{W} \tag{1}$$

where F is the surface of mass transfer (evaporation), m^2; W is the water weight, kg; k is the coefficient of proportionality (parameter of identification).

Let assume that in the first approximation Eq (1) is linear. In this case k=*const*.

This adjustment was added into the developed models of nonstationary mass transfer upon natural (Konstantinov et al. 2015) and forced (Korotkova et al. 2016b) convection, the water evaporation in time was calculated. The calculations using the models are iterative. As a consequence of achievement of certain moisture weight, the initial increment (decrement) of ΔF_nsurface is calculated at the n-th step by F_{n-1} and W_{n-1} at previous step n-1 according to Eq. (1):

$$\Delta F_n = k\Delta W_{n-1}\frac{F_{n-1}}{W_{n-1}} \tag{2}$$

Then the surface F_n is calculated at the n-th step:

$$F_n = F_{n-1} - \Delta F_n \tag{3}$$

On the basis of analysis of curves of moisture evaporation, the weight of 1 g (Korotkova et al. 2016a) for natural convection and 2 g (Danilchenko, Korotkova 2016) for forced convection were selected as the weights at which the evaporation surface started to decrease. The identification parameter for natural and forced convection was k = 0.7.

Figure 4 compares experimental data and calculated curve of water evaporation at natural convection at 55°C in drying oven. The time interval of water heating can be obviously seen in Figure 4, its calculated value is 21 min. The calculated temperature of water surface during heating varied from 25°C to 32.9°C where 25°C was the initially measured temperature. At 60°C in drying oven the calculated temperature of water surface during heating varied from 25.5°C to 34.7°C (Figure 5) where 25.5°C also correspond to the initially measured temperature.

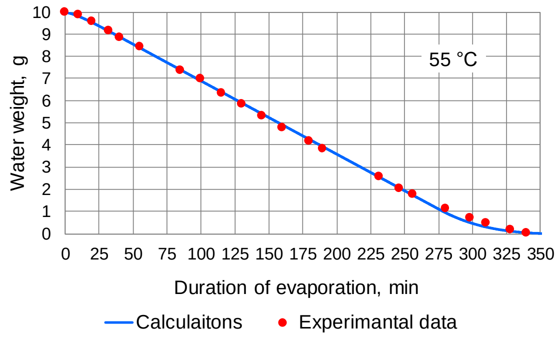

Figure 4: Water Evaporation Curve under Natural Convection at the Temperature of DryingAgent of 55°C

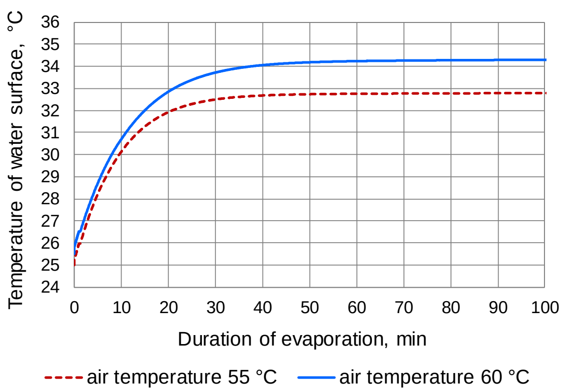

Figure 5: Calculated Temperatures of Water Surface During Heating under Natural Convection

Similar comparison upon forced convection at various temperatures is illustrated in Figure 6 (experimental data (Danilchenko, Korotkova 2016)). In (Korotkova et al. 2016c) we experimentally demonstrated that upon forced convection in comparison with natural one, the temperature of wet thermometer during removal of free moisture was higher and increased with the increase in the temperature of drying agent which was confirmed by the data in (Terekhov, Shishkin 2009).

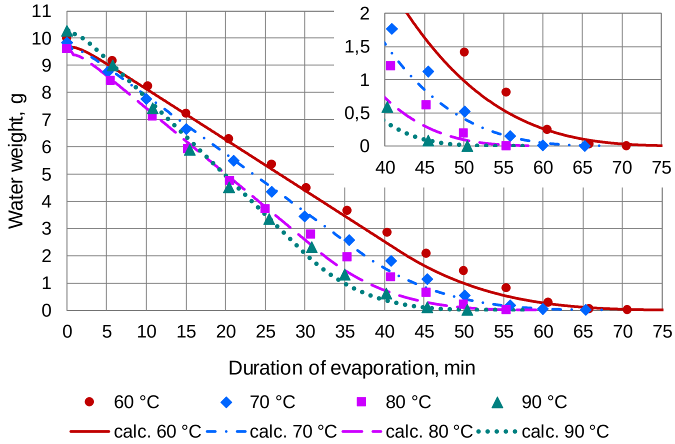

Figure 6: Water Evaporation Curve at Various Temperatures upon Forced Convection (Celsius Temperature: Drying Agent)

Evaporation rates as a function of water weight loss upon natural and forced convection are illustrated in Figures 7 and 8, respectively, where the temperature corresponds with the temperature of drying agent. During water heating the drying rate increases and remains constant during overall process of its evaporation. The evaporation was assumed to be terminated when water weight became less than possible weight measurements on balance with the accuracy of 0.1 mg.

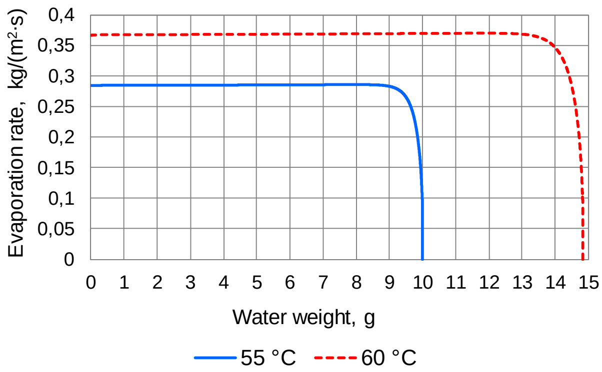

Figure 7: Evaporation Rate as a Function of Water Weight Loss upon Natural Convection (Celsius Temperature: Drying Agent)

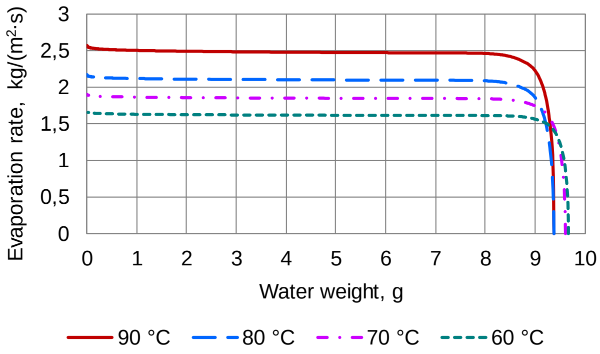

Figure 8: **Evaporation Rate as a Function of Water Weight Loss upon Forced Convection (Celsius Temperature: Drying Agent)**

Figure 9 illustrates evaporation rate as a function of drying agent (air) temperature. The higher is the temperature of drying agent, the higher is the evaporation rate which agrees with the numerous results of other researchers.

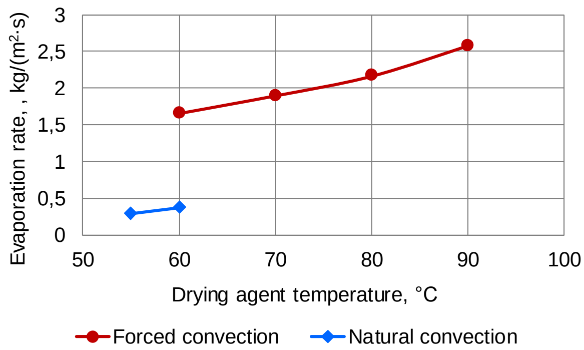

Figure 9: Evaporation Rate as a Function of Drying Agent Temperature

CONCLUSIONS

Evaporation rate of water from glass surface is *const*, which corresponds to the notion of evaporation rate of free moisture. Calculated losses of water weight in time with consideration for added correction agree with experimental data obtained under natural and forced convection. The evaporation rate increases during water heating and remains constant during overall evaporation process.

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